Title of Grant: **Dynamics and Morphology of Superfluid Helium Drops in a Microgravity Environment**

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Summary of Research

We developed an apparatus that makes it possible to observe and study magnetically levitated drops of superfluid helium. The force on a diamagnetic substance in a magnetic field is proportional to the gradient of the square of the magnetic field B. For the magnetic force on helium to be equal to the gravitational force on Earth, it is necessary for the product of B with the field gradient dB/dz to be 21.5 T^2/cm. In addition, in order for the magnetic field to provide a stable trap, the value of B^2 must increase in all directions in the horizontal plane that passes through the point where the field/field gradient product in the vertical direction has the critical value of 21.5 T^2/cm. A specially designed superconducting magnet that meets these specifications has been installed in a large helium dewar with optical access. Helium drops levitated by the magnet can be viewed along the axis of the solenoid. The sample chamber within the bore of the magnet is thermally isolated from the magnet and helium reservoir. Its temperature can be varied between 4 and 0.5 K, the lower part of the range being reached using a ^{3}He refrigerator. Liquid helium can be injected into the magnetic trap using a small capillary. Once a drop is contained in the trap it can be held there indefinitely.

With this apparatus we have conducted a number of different types of experiments on helium drops so as to gain information necessary for performing experiments in space. With magnetically levitated drops we are limited to working with drops of 1 cm or less in diameter. The shape of the drops larger than a few mm diameter can be distorted by the profile of the magnetic field. The study of phenomena such as the initial motion of the surfaces of two drops as they just make contact, requires the use large drops to resolve the behavior of interest.

We have performed a detailed investigation of the shape oscillations of superfluid drops. Shape oscillations were induced with an electric field in drops of approximately 0.5 cm diameter having a small positive charge. For a given size drop, it was possible to excite a large number of different normal modes by varying the drive frequency. For a spherical drop of radius R with a negligible density of the vapor outside the drop, the frequencies ω_l are given by the expression

$$\omega_l^2 = \frac{(l-1)l(l+2)\alpha}{\rho R^3}$$

where α is the surface tension, ρ is the density, and l=2, 3,.... We are able to detect modes with l up to 15, and through the use of lock-in techniques can measure the frequencies to an accuracy of about 1 part in 10^5. We found that when the amplitude of vibration is large, the resonant frequency decreases with increasing amplitude, as was observed by Rayleigh for classical drops. The damping of the oscillations was measured as a function of temperature. The time constant for damping for the lowest order mode was observed to vary from about 150 seconds at 1.7 K to less than 10 seconds at 0.7 K. The behavior of the damping rate could be understood quantitatively by a theoretical analysis. The motion of the liquid inside the drop is governed by the hydrodynamic equations of the two-fluid model, and the vapor around the drop is described by the classical Navier-Stokes equation. The velocity field for the normal fluid, the superfluid,

and the vapor are all expanded in terms of the appropriate Bessel functions. A key question in the calculation is how to make the correct choice of the boundary conditions to apply at the surface of the drop. The flux of mass and energy must be continuous across the liquid-vapor interface. The actual values of these fluxes are determined by the discontinuity in the temperature ΔT and in the chemical potential $\Delta\mu$ across the boundary together with the interfacial Onsager coefficients. The results of the calculation were found to be in excellent agreement with the measurements. The increase in the damping rate as the temperature decreases below 1 K is primarily due to the increase in the normal fluid viscosity in this temperature range.

In the course of making preliminary observations of the coalescence of helium drops we discovered that under certain circumstance do not coalesce but instead appear to rest against each other at the center of the trap. We were able to show that this effect is caused by a thin layer of vapor between the drops that prevented the liquid surfaces from coming into direct contact. The effect is thus similar to the Leidenfrost effect, which causes water drops to skate across a hot. The vapor layer exists because under the conditions of the experiments; the temperature of the cell walls is usually decreasing very slowly with time, thereby causing a slow evaporation of the drops. We have performed a calculation of the profile of the gap between the two drops, and found that the spacing of the liquid surfaces over most of the area was around 10 μm, but that there was a much narrower gap (~ 1 μm) at the edge. For the effect to occur, a small temperature gradient must exist within each of the two liquid drops. Thus, at temperatures below the lambda point where the thermal conductivity of the liquid is essentially infinite, the non-coalescence effect should not occur. This was confirmed experimentally.

We have also made a number of other measurements with the apparatus. These include some preliminary studies of the surface motion of a drop upon being formed by the coalescence of two drops. Also, we have investigated the rotation of superfluid drops. The motion of a superfluid with angular momentum is not the same as that of a classical fluid.

The results of this research have been documented in the publications listed on the following page.

Publications

"Magnetic Levitation of Liquid Helium", H.J. Maris, M.A. Weilert, D.L. Whitaker and G.M. Seidel, Czech. J. Phys. **46** Suppl. S1, 373 (1996).

"Magnetic Levitation and Non-Coalescence of Liquid Helium", M.A. Weilert, D.L. Whitaker, H.J. Maris, and G.M. Seidel, Phys. Rev. Lett. **77**, 4840 (1996).

"Magnetic Levitation of Liquid Helium", M.A. Weilert, D.L. Whitaker, H.J. Maris, and G.M. Seidel, J. Low Temp. Phys. **106**, 101 (1997).

"Oscillations of Charged Helium II Drops", D.L. Whitaker, M.A. Weilert, C.L. Vicente, H.J. Maris and G.M. Seidel, J. Low Temp. Phys. **110**, 173 (1998).

"Shape Oscillations in Levitated He II Drops", D.L. Whitaker, C. Kim, C.L. Vicente, M.A. Weilert, H. J. Maris and G.M. Seidel, J. Low Temp. Phys. **113**, 491 (1998).

"Theory of Small Amplitude Shape Oscillations of a Helium-II Drop", D.L. Whitaker, C.Kim, C.L. Vicente, M.A. Weilert, H.J. Maris and G.M. Seidel, J. Low Temp. Phys. **114**, 523 (1999).

"Coalescence of Levitated HeII Drops", C.L. Vincente, C.Kim, H.J. Maris and G.M. Seidel, J. Low Temp. Phys. **121**, 627 (2000).